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Abstract

The coercivity and exchange bias field of ferro-/antiferromagnetic Co 90Fe10/CoFe-oxide bilayers were studied as function of the surface morphology of the bottom CoFe-oxide layer. The CoFe-oxide surface structure was varied systematically by low energy (0-70 V) Argon ion-beam bombardment before subsequent deposition of the Co90Fe10 layer. Transmission electron microscopy results showed that the bilayer consisted of hcp Co90Fe10 and rock-salt CoFe-oxide. At low temperatures, enhanced coercivities and exchange bias fields with increasing ion-beam bombardment energy were observed, which are attributed to defects and uncompensated moments created near the CoFe-oxide surface in increasing amounts with larger ion-beam bombardment energies. Magnetometry results also showed an increasing divergence of the low field temperature dependent magnetization [ΔM(T)] between field-cooling and zero-field-cooling processes, and an increasing blocking temperature with increasing ion-beam bombardment energy. © 2012 The Japan Society of Applied Physics.

Keywords

correlating, moments, exchange, bilayers, oxide, interactions, coupling, cofe, antiferromagnetic, 10, co90fe, bombarded, beam, ion, interface, uncompensated

Disciplines

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Correlating Uncompensated Antiferromagnetic Moments and Exchange Coupling Interactions in Interface Ion-Beam Bombarded $Co_{90}Fe_{10}$ / CoFe-Oxide Bilayers

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Abstract

The coercivity and exchange bias field of ferro-/antiferromagnetic $Co_{90}Fe_{10}$ / CoFe-oxide bilayers were studied as function of the surface morphology of the bottom CoFe-oxide layer. The CoFe-oxide surface structure was varied systematically by low energy (0 – 70 V) Argon ion-beam bombardment before subsequent deposition of the $Co_{90}Fe_{10}$ layer. Transmission electron microscopy results showed that the bilayer consisted of hcp $Co_{90}Fe_{10}$ and rock-salt CoFe-oxide. At low temperatures, enhanced coercivities and exchange bias fields with increasing ion-beam bombardment energy were observed, which are attributed to defects and uncompensated moments created near the CoFe-oxide surface in increasing amounts with larger ion-beam bombardment energies. Magnetometry results also showed an increasing divergence of the low field temperature dependent magnetization [ΔM(T)] between field-cooling and zero-field-cooling processes, and an increasing blocking temperature with increasing ion-beam bombardment energy.

1. Introduction

Exchange bias [1-6], i.e., the shift of the hysteresis loop of a ferromagnetic (FM) material in contact with an antiferromagnetic (AFM) material after a field-cooling process, depends on many factors including the particular materials involved [7-10], film growth conditions [11-14], the structural, compositional and magnetic details of the interfaces [15-18], the magnetic stiffness of the AFM moments, and the field-cooling conditions [19-22].

In this work, we varied the structural and magnetic interface between FM and AFM $Co_{90}Fe_{10}$ / CoFe-oxide bilayers by bombarding the surface of the bottom AFM CoFe-oxide layer with Argon ions of varying energy before the subsequent growth of the top FM $Co_{90}Fe_{10}$ layer. We observed a systematic increase of the coercivity and exchange bias at low temperature as function of the Ar ion-beam energy, which we attributed to an increase in the creation of defects and uncompensated moments in the AFM layer from higher ion-beam energies.

2. Experimental Methods

The $Co_{90}Fe_{10}$ (at%) / CoFe-oxide bilayers were prepared on oxidized Si wafer substrates by using a dual ion-beam sputtering deposition technique [21,22]. A Kaufman ion source (800 V, 7.5 mA) was used to focus an Argon ion-beam onto a commercial $Co_{90}Fe_{10}$ target surface in order to fabricate the top $Co_{90}Fe_{10}$ layer. An End-Hall ion source (V_{EH} = 100 V, 500 mA) was used to in-situ bombard the growing bottom layer during deposition with a mixture of 41% O_2 / Ar (O_2/Ar flow rate: 1.6/2.3 sccm) in order to fabricate the bottom CoFe-oxide layer (17 nm nominal thickness). Before capping with the top $Co_{90}Fe_{10}$ layer (23 nm nominal thickness), the surface of the CoFe-oxide layer was bombarded by 100% Ar ions using the same End-Hall source. The acceleration voltage (V_{EH}) was varied from 40 to 70 V for different films in order to create varying surface microstructure on the CoFe-oxide layer.

3. Results and Discussion

The microstructures of the $Co_{90}Fe_{10}$ (~17 nm) / CoFe-oxide (~23 nm) bilayers were characterized by TEM (Transmission Electron Microscopy), as shown in Fig. 1. The un-bombarded (V_{EH} = 0 V) $Co_{90}Fe_{10}$ / CoFe-oxide bilayers were polycrystalline with grain sizes ranging from 5 to 15 nm. The respective electron diffraction patterns [Fig. 1(a)] indicated that the bilayers consisted of hcp $Co_{90}Fe_{10}$ (a~ 2.5 Å, c~ 4.1 Å) and rock-salt CoFe-oxide (a~ 4.2 Å), in agreement with our previous works [22,23] on these CoFe-based film systems. The bombardment of the bottom CoFe-oxide layer surface with low-energy Ar ion-beams (V_{EH} = 40 to 70 V) neither changed the crystal structure nor altered significantly the grain size distribution close to the CoFe-oxide surface, as revealed by the TEM images and diffraction patterns shown in Figs. 1(c) and 1(d) for $Co_{90}Fe_{10}$ / CoFe-oxide (V_{EH}= 50 V) and Figs. 1(e) and 1(f) for $Co_{90}Fe_{10}$ / CoFe-oxide (V_{EH}= 70 V). As can be seen in the cross-sectional TEM images in Figs. 1(b), 1(d) and 1(f), all $Co_{90}Fe_{10}$ / CoFe-oxide bilayers exhibited a smooth interface with roughnesses considerably below 2 nm. It can be concluded from the data presented in Fig. 1 that the low-energy ion-beam bombardment did not lead to significant microstructural and morphological variations (lattice constant, grain size, roughness, and interface flatness) in the AF CoFe-oxide layer.

The room temperature hysteresis loops of the different $Co_{90}Fe_{10}$ / CoFe-oxide bilayers made with Ar ion-beam bombardment voltages, V_{EH} = 0 to 70 V, are shown in Fig. 2. Since $Co_{90}Fe_{10}$ is a ferromagnet ($T_{c,\ bulk}$~ 1800 K [24]) and CoFe-oxide is an antiferromagnet with a Néel temperature less than that of CoO ($T_{N,\ bulk}$~ 290 K [25]), no exchange bias effects were expected at room temperature. The $Co_{90}Fe_{10}$ / CoFe-oxide bilayer without ion-beam bombardment (V_{EH}= 0 V) exhibited a square hysteresis loop with a high remanence magnetization, M_r, and a coercivity of H_c ~ 15 Oe, as is shown in Fig. 2(a). Increasing the ion-beam bombardment energy [Fig. 2(b)] resulted in a systematic decrease of M_r, while H_c remained unaffected (~20 Oe).

The decrease in M_r with increasing V_{EH} indicates that the ion-beam bombardment of the bottom CoFe-oxide layer may have created defects that influenced strongly the magnetization reversal processes in the $Co_{90}Fe_{10}$ layer. Since the CoFe-oxide layer is believed to be paramagnetic at 298 K, structural defects [26] must have been responsible for the low M_r values of the ion-bombarded samples.

To study exchange bias effects, the $Co_{90}Fe_{10}$ / CoFe-oxide bilayers were 12 kOe field-cooled from 350 to 50 K. The hysteresis loops for the films after field cooling are shown in Fig. 2(c). In contrast to the room temperature behavior, for all V_{EH}

bombardment energies, a square and symmetric loop shape was present, and a high remanence concomitant with the square loops, i.e. M_r / M_s ~ 1. Figure 2(c) identifies clearly that an increasing exchange bias field (H_{ex}) developed with increasing ion-beam bombardment energy. The dependence of H_c and H_{ex} on V_{EH} [Fig. 2(d)] shows that without ion-beam bombardment, H_{ex}~ -150 Oe and H_c~ 250 Oe was measured, and for increasing V_{EH} values up to 70 V a monotonic increase of H_c and H_{ex} resulted. These trends contrast those observed in a previous study on films of similar composition with modifications of the interface [23]. Using much higher ion-beam bombardment energies of V_{EH}= 70 - 150 V, caused greater damage to the AF spin configuration in the CoFe-oxide layer and increased in the degree of misalignment [27,28], which resulted in a decrease of H_{ex}. In addition, the linear increase of H_c vs V_{EH} in the $Co_{90}Fe_{10}$ / CoFe-oxide bilayers in this study indicates that an enhancement of the $Co_{90}Fe_{10}$ anisotropy could be achieved by coupling to the defects created by ion-beam bombardment on the AF CoFe-oxide surface that act as pinning sites of domains during the magnetization reversal processes [21].

Further evidence of the nature of the exchange coupling between the $Co_{90}Fe_{10}$ and CoFe-oxide layer is evident in the temperature dependence of the zero field-cooled (ZFC) and field-cooled (FC) DC susceptibility (M vs T) data measured with a Quantum Design VSM using 100 Oe, as shown in Fig. 3. The difference in the ZFC/FC curves is small (e.g., consider the ΔM_{FC-ZFC} in Fig. 4) in $Co_{90}Fe_{10}$ / CoFe-oxide bilayers without (V_{EH}= 0 V) or with low energy ion-beam bombardment (V_{EH} = 40 and 50 V). However, a significant increase in the ZFC moment with increasing temperature from 50 to 300 K was observed for the largest V_{EH}= 70 V [Fig. 3]. This parallels the change in the ferromagnetic response as a function of temperature, and is a signature of the exchange coupling between the $Co_{90}Fe_{10}$ and the CoFe-oxide layer, identified by its larger H_{ex}. Note that a similar effect was also observed in NiFe/NiFeO thin films [29]. The blocking temperature, T_B, estimated by the magnetization with a maximum in the ZFC scan [29], was found to increase with increasing V_{EH} from 180 K (V_{EH} = 0 V) to 230 K (V_{EH} = 70 V), as shown in the inset of Fig. 3.

Our previous work on NiFe/NiO bilayers [21] has shown that the pure ferromagnetic (e.g., permalloy) layer usually exhibited identical ZFC and FC curve with H_{app} = 100 Oe (i.e. $\Delta M_{FC\text{-}ZFC}$(T)= 0), while the coupling of the FM layer with an AFM layer like NiO will result in a clear divergence between M_{ZFC}(T) and M_{FC}(T). In the present study, a similar behavior was found in which the degree of divergence ($\Delta M_{FC\text{-}ZFC}$) seems to depend strongly on the ion-beam modification of exchange bias, as demonstrated by the increase of $\Delta M_{FC\text{-}ZFC}$ (at 50 K) with increasing V_{EH}, as shown in Fig. 4.

The degree of exchange coupling is qualitatively estimated by the difference in magnetization (Δ) [29] between FC and ZFC at 50 K, which is about 3% in a spin (or cluster) glass [30] and about 0.5% in a pure permalloy layer [29]. The $Co_{90}Fe_{10}$ / CoFe-oxide (V_{EH}= 70 V) bilayer exhibited the largest difference in magnetic moment (Δ~ 40%), compared to those of Δ (<10%) in the $Co_{90}Fe_{10}$ / CoFe-oxide bilayers with CoFe-oxide surface being bombarded by lower energies (40 and 50 V) or without bombardment (Δ~ 3%). The $Co_{90}Fe_{10}$ / CoFe-oxide (V_{EH}= 70 V) bilayer also had the highest exchange bias, and lowest room temperature remanence M_r. Therefore, the difference (Δ) in magnetic moment at 50 K between ZFC and FC curves is a measure of the onset of exchange coupling between FM $Co_{90}Fe_{10}$ and AFM CoFe-oxide, which altered the ferromagnetic properties. Moreover, it is clear that the temperature where this occurred depended on the ion-beam bombardment energy, implying the formation of differing amounts of stable uncompensated AF CoFe-oxide moments with differing ion doses.

4. Conclusions

Low-energy Ar ion-beam bombardment was used to modify the exchange bias effects of $Co_{90}Fe_{10}$ / CoFe-oxide bilayers. At low temperature, the $Co_{90}Fe_{10}$ / CoFe-oxide bilayers exhibited an almost linear increase of coercivity and exchange bias field with increasing Ar ion-beam bombardment energy on the bottom CoFe-oxide surface. This indicated that the ion-beam bombardment of the CoFe-oxide surface created defects that acted as pinning sites to affect the magnetization reversal processes in $Co_{90}Fe_{10}$, thus resulting in coercivity enhancements. This process also promoted the formation of thermally-stable uncompensated moments near the surface of the bottom CoFe-oxide layer that permitted exchange bias loop shifts.

Acknowledgments

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Figure captions

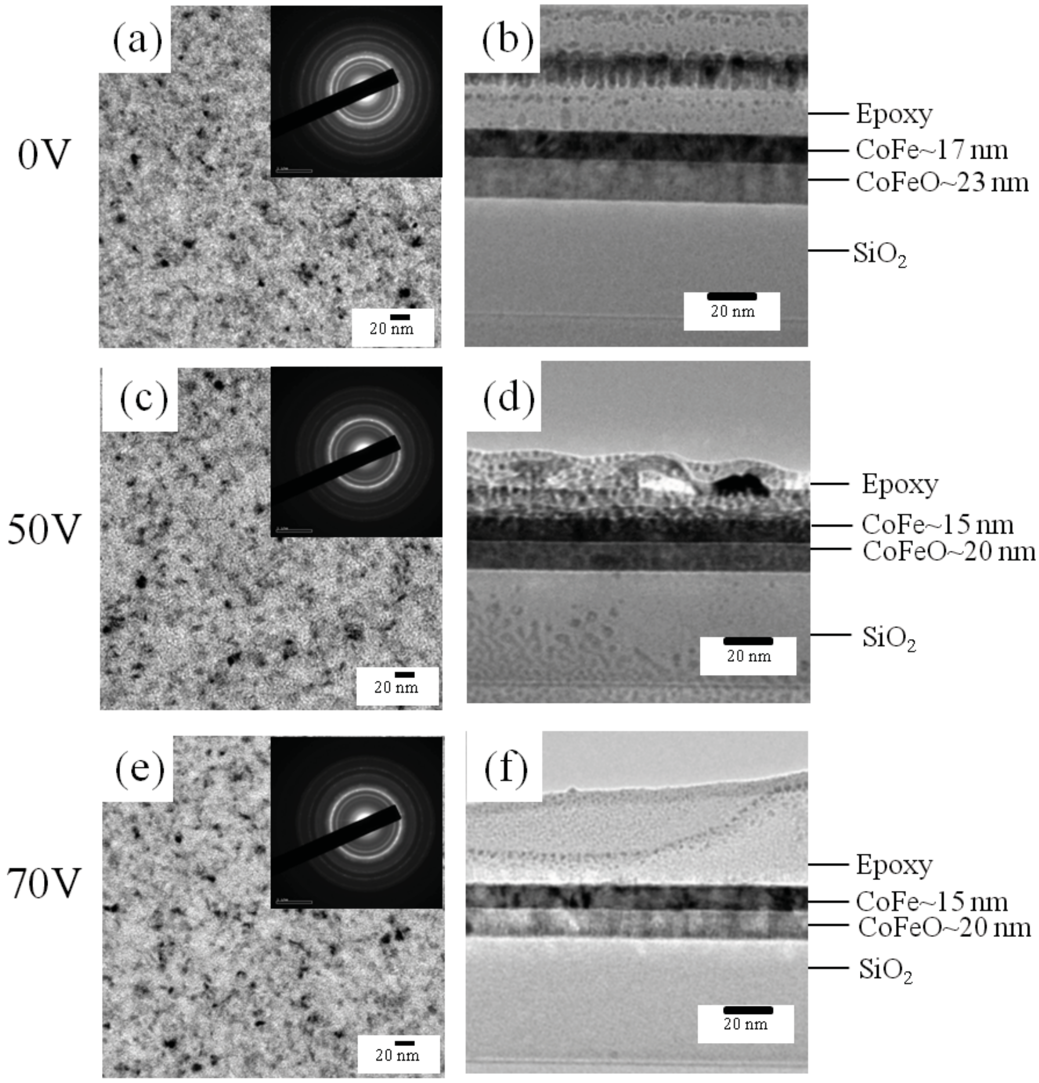
Fig. 1. The planar-view TEM micrographs of the bottom CoFe-oxide layer with Ar ion-beam bombardment on the surface with different energies (V_{EH}) of (a) 0 V, (c) 50 V, and (e) 70 V. The cross-sectional TEM micrographs of the $Co_{90}Fe_{10}$ / CoFe-oxide bilayer with the bottom layer bombarded with different V_{EH} are shown in (b) 0 V, (d) 50 V, and (f) 70 V, respectively.

Fig. 2. Hysteresis loops of $Co_{90}Fe_{10}$ / CoFe-oxide (V_{EH}= 0, 40, 50, and 70 V) bilayers measured at (a) 298 K and (c) 50 K (after FC in 12 kOe). (b) Remanent magnetization M_r at 298 K as function of V_{EH}. (d) Dependence of H_c and H_{ex} on V_{EH} at 50 K after FC.

Fig. 3. The temperature dependence of ZFC and FC magnetization of $Co_{90}Fe_{10}$ / CoFe-oxide bilayers. The blocking temperature vs V_{EH} is shown in the inset.

Fig. 4. The temperature dependence of the difference between ZFC and FC magnetization ($\Delta M_{FC\text{-}ZFC}$) of $Co_{90}Fe_{10}$ / CoFe-oxide bilayers. The $\Delta M_{FC\text{-}ZFC}$ at 50 K vs V_{EH} is shown in the inset.

Fig. 1.



(a)
(b)
0V
Epoxy
CoFe~17 nm
CoFeO~23 nm
SiO2
20 nm
20 nm
(c)
(d)
50V
Epoxy
CoFe~15 nm
CoFeO~20 nm
SiO2
20 nm
20 nm
(e)
(f)
70V
Epoxy
CoFe~15 nm
CoFeO~20 nm
SiO2
20 nm
20 nm

Fig. 2.

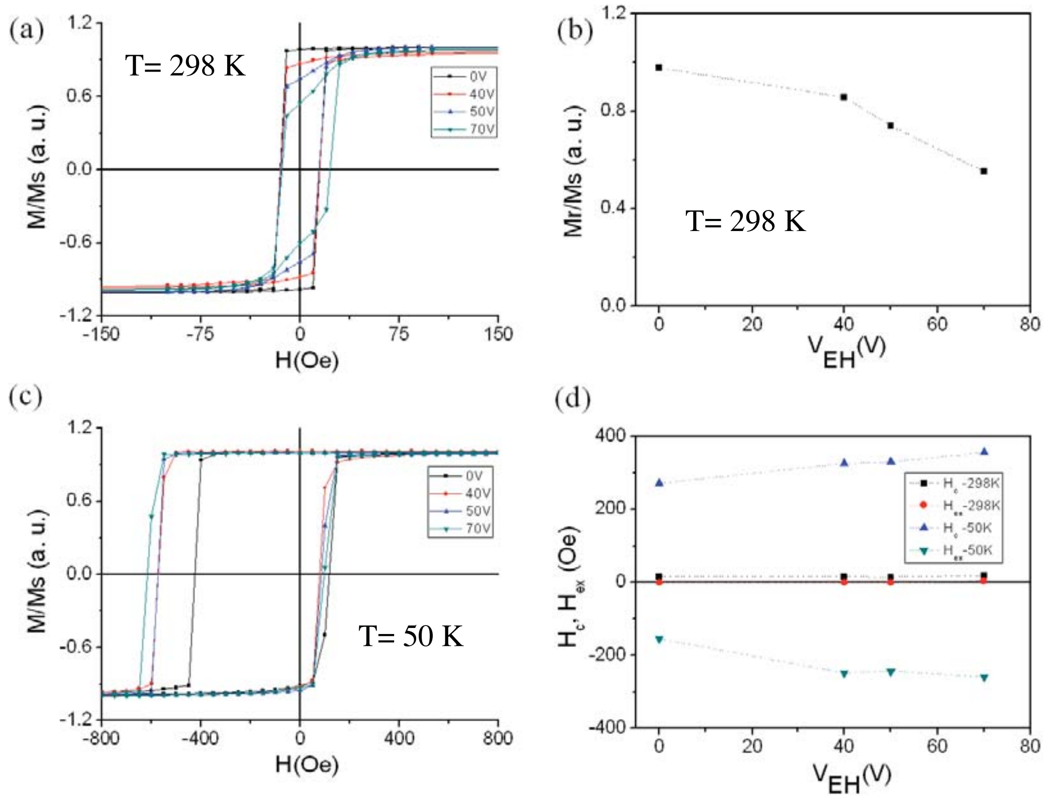
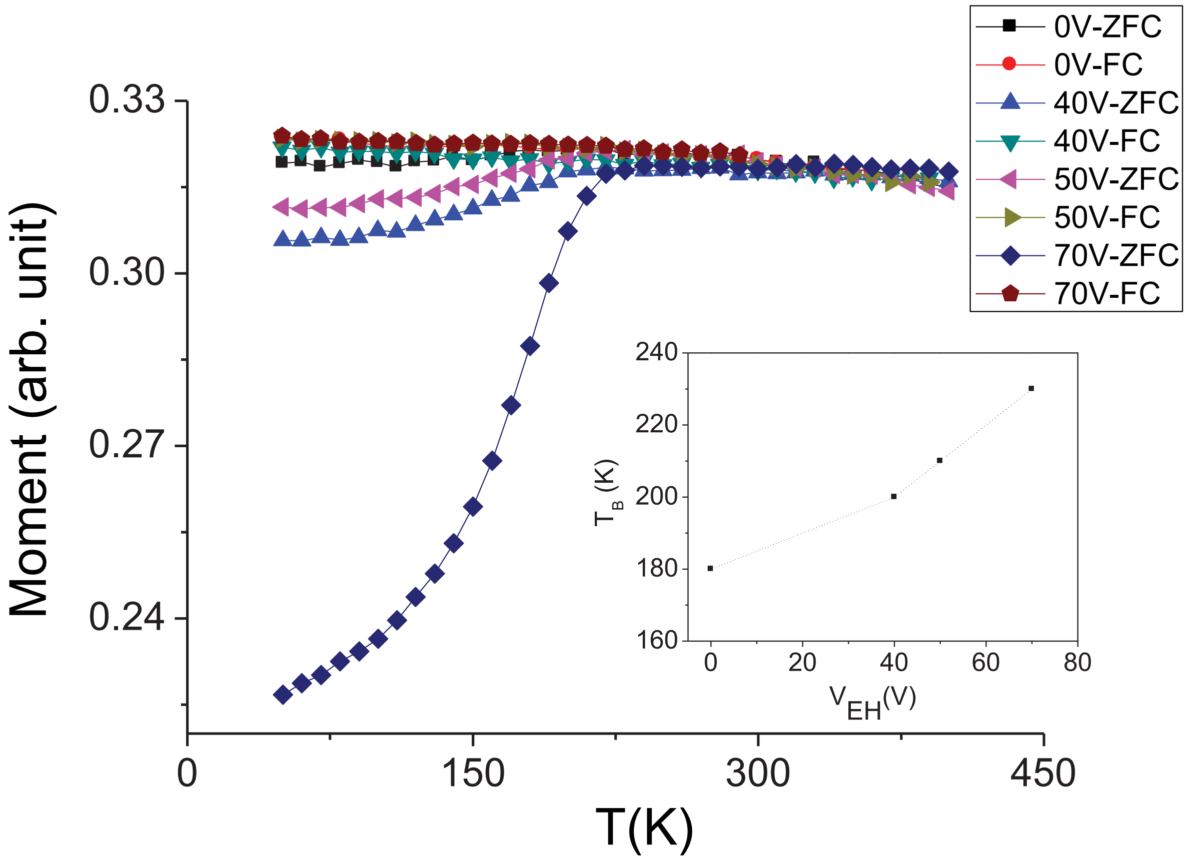
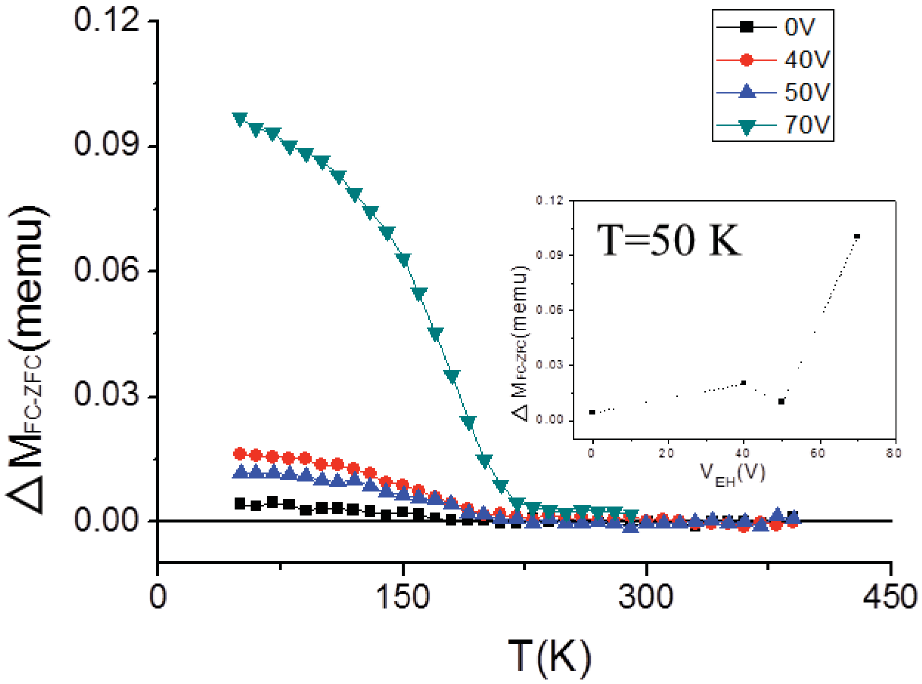

(a)
T= 298 K
0V
40V
50V
70V
M/Ms (a. u.)
H(Oe)
(b)
T= 298 K
Mr/Ms (a. u.)
V_{EH}(V)
(c)
T= 50 K
0V
40V
50V
70V
M/Ms (a. u.)
H(Oe)
(d)
H_c-298K
H_{ex}-298K
H_c-50K
H_{ex}-50K
H_c, H_{ex} (Oe)
V_{EH}(V)

Fig. 3.



0V-ZFC
0V-FC
40V-ZFC
40V-FC
50V-ZFC
50V-FC
70V-ZFC
70V-FC
0.33
0.30
0.27
0.24
Moment (arb. unit)
0
150
300
450
T(K)
240
220
200
180
160
T_B (K)
0
20
40
60
80
V_{EH}(V)

Fig. 4.



0.12
0.09
0.06
0.03
0.00
ΔM_{FC-ZFC}(memu)
0
150
300
450
T(K)
0V
40V
50V
70V
T=50 K
ΔM_{FC-ZFC}(memu)
V_{EH}(V)